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Classification of discarded NiMH and Li-Ion batteries and reuse of the cells still in operational conditions in prototypes

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HIGHLIGHTS

- Significant amount of batteries are discarded before the end of its useful life.
- Discarded NiMH and Li-Ion cells were compared to new cells.
- Charge capacity of assessed cells showed acceptable operational conditions.
- The reuse of batteries cells is encouraged in academic manufacturing of prototypes.
- The methodology is in line with the challenge of promoting the reuse of cells.

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ABSTRACT

The growing production of high-tech devices is strongly associated to a great waste of natural resources and to environmental contamination caused either by the production process of such devices as the quick disposal of them. Cell phones have stood out from the most commercialized electronic devices, which have increased the demand for rechargeable batteries which are afterward discarded before the end of its useful life. The main objective of this paper is to improve a methodology for classify the amount of NiMH and Li-Ion batteries discarded still in operating condition through concepts given to the cells. Tests with 3 NiMH and 3 Li-Ion different battery models were done. This paper also aimed to promote the efficient use of batteries cells through their reuse in academic activities related to the manufacturing of prototypes. It presents the construction of an illuminator and of a portable power supply. The results obtained showed that approximately 40% of NiMH cells and 45% of Li-Ion cells assessed were in operational condition, with charge capacity between 62% and 90%, when compared to a new cell. Such results warn about the waste of natural resources and the proposal to test the same before the final disposal.

1. Introduction

Today's society lives up against a paradox that must be solved in short term: Solving the matter of the growing production of high tech devices, more and more accessible, associated to the waste of natural resources and to environmental contamination caused either by the production process of such devices as the quick disposal of them. Be it due of its quick obsolescence or because they are damaged, they have been discarded in landfills or other inappropriate places where the ways to reuse them are crude and precarious. It is associated to this, the lack of a regularization policy of the waste from these devices, or at most a modest set of legal devices that do not meet minimally the real needs of environmental preservation, causing damages already duly found in the very human health, including in countries that are considered developed [1]. Mobile phone is among the electronic devices that have won consumers worldwide in a quick way, reaching 50 million users in five years. Television took thirteen years to reach a similar public. Out of the world's estimated 7 billion people, 6 billion have access to mobile phones – equivalent to more than 85% of global population. According to Anatel (Agência Nacional de Telecomunicações) a national telecommunications agency, in February of 2013, Brazil reach 263,04 million qualified access [2].

Silveira et al. [3] presents an overview of cell phone recycling programs currently available in the United States and provides analyses of the current recycling situation and possible recycling

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alternatives for Brazil. A deposit/refund/advance-recycling fee is proposed which might be implemented as a voluntary industrial initiative managed by PRO Brazil, a producer responsibility organization. However, at the beginning of an extended producer responsibility process, producers will certainly need to invest a considerable amount of financial resources. According to Oliveira et al. [4], the main difficulty associated with the implementation of e-waste recycling processes in Brazil is the collection system, as its efficiency depends not only on the education and cooperation of the people but also on cooperation among industrial waste generators, distributors and the government.

Most of the components of the cell phone are very small: the speaker is about the size of a dime and the microphone is no larger than a watch battery. But these, too, contain heavy metals and hazardous materials. The case is made of plastics – usually polycarbonate (PC), acrylonitrile butadiene styrene (ABS), or a combination of the two. Recycling of these plastics is hampered by additives, particularly brominated flame retardants. Studies so far indicate that the environmental impacts of these components are dwarfed by those of the printed wiring board and liquid-crystal display [5].

The adapter used to charge the batteries may weigh more that the handset itself and is a major contributor to cell phone waste. Little analysis has been performed on the composition and environmental impacts of this component. Adapters consist mainly of copper wires encased in plastic, but materials such as gold, cadmium, and brominated flame retardants may also be present. In addition, the adapter often weighs more than the handset and batteries combined. Since each phone comes with its own adapter, which generally cannot be used with other makes and models, this device can add substantially to the waste generated by discarded cell phones.

Persistent, Bioaccumulative, and Toxic Chemicals (PBTs) found in cell phones include arsenic, antimony, beryllium, cadmium, copper, lead, nickel, and zinc. (Cell phones also contain toxic substances not included on the EPA's list of PBTs, such as brominated flame retardants.) PBTs are persistent in that they linger in the environment for a long time without degrading, increasing the risk of exposure to human beings. They can also spread over large areas, moving easily between air, water, and soil, and have been found far from the areas in which they were generated. PBTs accumulate in the fatty tissues of human beings and other animals, increasing in concentration as they move up the food chain. As a result, they can reach toxic levels over time, even when released in very small quantities [6].

The time required for batteries to reach the end of their life cycle depends on the frequency of recharge, what is related to its capacity, the device consumption and the way it is used (how the user recharges it). Considering that 350 and 490 charge and discharge cycles are equivalent to the useful life of NiMH and Li-Ion batteries, respectively, for NiMH batteries, it would be equal to a useful life of more than two years, in the case of three recharges a week, and more than 6 years if recharged only once a week. As for Li-Ion batteries, they would have an average life cycle of more than three years, in the case of three recharges a week, and more than nine years if recharged only once a week [7]. Along with most of these devices, their batteries ends up running out of use before reaching the end of their life cycle, just because they do not match the new model of device.

An important factor that strongly affects cell performance or capacity is the internal impedance of the cell, promoting voltage drop during operation, which in turn also consumes part of the useful energy as heat loss. This voltage drop due to internal impedance is usually referred to as ohmic polarization or IR drop and is proportional to the current consumed by the system. Overall internal impedance of a cell is the sum of the ionic resistances of the electrolyte (inside the separator and the porous electrodes) and the electrical resistance of the active mass, the current collectors and the electrical contacts of both electrodes, as well as of the contact resistance between active mass and current collector. The useful voltage provided by cells is reduced by polarization and IR drop. Polarization and IR drop are small only at very low levels of operating current, when the cell operates near open-circuit voltage and delivers a great part of the theoretically available energy.

Impedance is influenced by a number of factors, such as temperature, discharge depth, state of charge (SOC), and constructive factors, being thus difficult to measure. The ideal model is a resistance connected in series with an inductance and a parallel capacitance. Resistance may be indirectly measured by reading the voltage over battery terminals divided by the current circulating in the battery, and may be used several times as an indicator of the SOC of the battery, because the inductive and capacitive effects are almost always disregarded, since batteries are direct current devices [8].

In order to measure internal resistance, two measures should be obtained: firstly, with the device disconnected from any charge, i.e., null current (open-circuit voltage) and then with the device connected to a given charge. Considering a Thevenin equivalent voltage, in which the battery represents an ideal source with an internal resistance, it is possible to calculate this resistance based on these two measures. The internal resistance of a battery at a particular point in time is the voltage derivative with respect to time divided by the current circulating in the battery at this same point in time. In the process of battery recharge, the voltage over the battery increases less and less over time, yielding an exponential growth curve tending to saturation, and battery internal resistance decreases. Similarly, its internal resistance increases during discharge.

Batteries are perishable products that deteriorate as the result of a chemical action during storage. Design, electrochemical system, temperature, and duration of the storage period are factors that affect their shelf life or their charge retention. All batteries present a certain amount of self-discharge, especially the nickel-based ones. As a general rule, a nickel-based battery self-discharges nearly 10% of its capacity within the first 24 h of use and nearly 10% during each subsequent month. The self-discharge rate of Li-Ion batteries is lower, totaling 5% within the first 24 h of use and from 1 to 2% during each subsequent month. Battery self-discharge increases gradually with high temperature, improvement in battery cycle, age, and presence of a protection circuit. In high cycling batteries, there is a higher energy loss through self-discharge than through actual use and, in these cases, this effect is irreversible [9,10].

As batteries get old, their state of health (SOH) decreases and their impedance increases, which leads to a decrease in their SOC. The SOC of a battery is related to its maximum available capacity and not to its nominal capacity. Accurate knowledge of SOC provide an additional control over the charging and discharging process and may be used to improve battery life, reducing thus the risk of overvoltage and gassing, which degrade the battery. Previous studies have established a relationship between variation in impedance and SOC, but this was problematic in the region from full to partial SOC, because impedance changes in this region were small, which lead to inaccurate results [11,12].

According to Bernardes et al., most batteries of domestic use, specially the primary ones, in other words, those that cannot be recharged are discarded in landfills of urban solid waste. In order to make the battery recycling, it is first of all necessary to know its composition [13]. Wanga et al. [14] carried out an economic modeling and fundamental material characterization methods to quantify economic trade-offs for lithium ion batteries at their end-

of-life. Many studies have been conducted aiming the development of processes to recycle used batteries or, in some cases, treat them for a safe disposal [15–22].

However, the reuse of battery cells that still have operational condition or yet, alternatives to increase the usage time of a battery should be considered, considering the high value added to this kind of energy storage and conversion device. In this context, this article proposes the assessment of discarded batteries from the use of a bench designed for testing and from the application of an improved methodology for separation and classification of NiMH and Li-Ion batteries cells [23].

1.1. Materials and components in prototypes

In universities, the easy access to new and varied technologies stimulate the creativity of students in the development of innovative solutions to design problems. Undergraduate and postgraduate apply their expertise in product design, and using models and prototypes, perform tests and trials at the academic level. For prototyping often there is a difficulty in acquiring parts and materials specified in the design. Main barriers to the application of certain technologies can cite the high cost and unavailability of materials and components in the national market. A good opportunity to acquire materials, parts, components, devices and systems is through reuse. The reuse strategy implemented in the prototype development allows increasing the materials lifetime and components and assist designers in constructing prototypes.

This paper also proposes the reuse of approved cells as devices for energy storage and power supply for prototypes, as a light fixture. Therefore, this paper contributes to the reduction of waste of batteries with potential for reuse, providing an efficient and environmentally sustainable alternative where they can be used to decrease the huge amount of waste generated by this kind of technology.

2. Materials and methods

2.1. Classification of discarded batteries

To assess the percentage of small rechargeable batteries that have been discarded before reaching the end of their useful life, discarded batteries collected from collection center of the manufacturing companies. Batteries were separated by model and thereafter, an improved characterization methodology was applied based on four stages (disassembly, assessment of the visual aspect, voltage checking and assessment of charge retention in the cycles) [23]. As shown in Fig. 1, the present work attempt to encourage the reuse of the batteries cells still in operational conditions in academic activities related to the manufacturing of prototypes.

For the batteries disassembly, a workstation composed by an illuminated bench with tools to force the joints in the most fragile parts of the cover, to remove either the cells as the pressed circuit boards (PCI's) contained in batteries. Table 1 lists the battery models studied and its respective amounts. These NiMH and Li-Ion battery models were chosen due to their greater availability among the collected batteries.

At the second stage, an analysis of the superficial aspects was done in order to identify, through visual inspection, the cells that had leakage or oxide layer or deformation (bloating). The detection of any of these aspects that were mentioned characterized the cells as degraded and, therefore, dismissed as an object for this study.

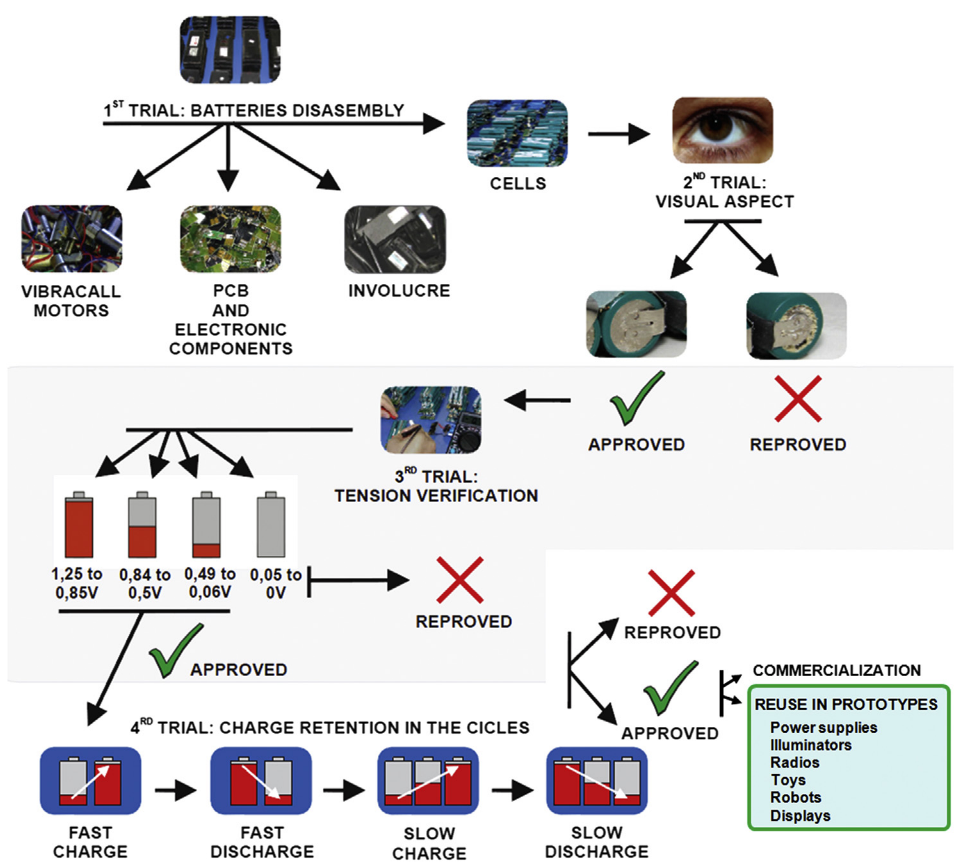

Fig. 1. Phases of the assessment process for cells considered reusable and their reuse in academic activities related to the manufacturing of prototypes.

Table 1
Models of the batteries that were studied and their respective amounts.

Brand	Model	System	Capacity (mA h)	Quantity	Representative photo
Nokia	BMS-3	NiMH	1000	237	
Nokia	BMC-3	NiMH	900	97	
Ericsson	BKB 193 (1-105)	NiMH	900	65	
Nokia	BL-5C	Li-Ion	850	97	
Siemens	V30145-K1-X250	Li-Ion	700	62	
LG	LGIP-G830	Li-Ion	830	68	

The cells approved by the visual inspections moved to the third stage of the process, where the remaining voltage of the cells were measured, and thus, classified, identified and separated according to the respective voltage value, as shown in Table 2. The cells that had voltage values between 0.05 and 0 V were rejected.

At the stage of performance tests in charge and discharge cycles, a battery test bench design and built for assessment of cells that were classified at the previous stages as in operational. The cell with medium or high remaining charge were then discharged until reaching a low level of charge and then connected to the test bench where they were subjected to two cycles of charge and discharge.

Batteries were charged by the constant current method, using limited currents, in order to avoid an excessive increase in temperature and not to exceed the reaction rate for oxygen recombination, since it is detrimental to cells and may degraded them. Current values and cycle duration were defined so that to apply not very deep charges and discharges, with the purpose of increasing the life cycle of the cells. It was taken into account that the highest capacity levels may be achieved with 150% of input charge and the maximum life cycle is achieved with 120% of input charge, but with lower capacity due to insufficient input charge [7].

Table 2
Classification given at the 3rd stage according to the remaining voltage values of each cell approved at the previous stage.

Classification	NiMH (V)	Li-Ion (V)
CA	1.25–0.85	3.8–2.5
CM	0.84–0.5	2.49–1.31
CB	0.49–0.06	1.3–0.11
CZ	0.05–0	0.1–0

Data were registered for the assessment of the performance of each cell. At this stage the cells were classified according to the charge presented after the cycles of quick and slow charge and discharge depending on the voltage levels shown in Table 3. Cells were then wrapped in order to be stored and subsequently reused, with special care to the negative and positive poles, which were protected with insulating tape.

2.2. New batteries with cells approved for reuse

The large variety and availability of cells with capacity for reusability allows the formation of batteries with different voltages, capacities and dimensions, each having a more favorable performance under specific operating conditions. The characteristics of every possible battery resulting from the combination of cells available should be compared with the requirements of the equipment to select the one that best meets those needs. It is important to note that the selection of cells for reuse can occur in two cases:

1. The first relates to the reuse of cells in existing products, where both the compartment and the specifications are already defined;
2. The second is use in developing new products. The latter case is preferable, because the selection is made early in the development of the equipment rather than at the end when the hardware is already fixed. This is due to the fact that in this way, the compromise between the properties of batteries and the equipment requirements can be obtained more effectively.

The other considerations that are important and influence the selection of secondary battery cells for reuse include:

1. Electrochemical system: comparing the advantages and disadvantages of the characteristics of same with the requirements of the equipment;
2. Voltage: rated or operating voltage, maximum and minimum values, adjustment, profile of the discharge curve, time for the start of operation, voltage drop;
3. Service time: the amount of time required for operation;
4. Physical requirements: size, shape, weight, terminals;
5. Operating conditions: vibration, shock, rotational movements, acceleration, etc; atmospheric conditions (pressure, humidity, etc.), temperature range in which the operation is required;

Reuse of cells is not appropriate where the operation will occur in severe or potentially dangerous conditions such as storage, standby or operation in extreme temperatures, or high reliability applications such as special applications where voltage drops are not admissible.

Applications for batteries can be divided into three main categories: the applications for handheld devices, industrial applications (where usually large size batteries are used) and in uninterruptible power supplies (UPS) for computers or other sophisticated systems that require extremely reliable operation, and

Table 3
Concepts given to the cells qualifying their performance after the slow charge and discharge cycles according to voltage levels.

Concept		A	B	C	D	E	F	FF
Voltage (v)/cell	NiMH	1.45–1.1	1.09–0.9	0.89–0.7	0.69–0.5	0.49–0.3	0.29–0.1	0.09–0
	Li-Ion	4.5–3.3	3.29–2.7	3.69–2.1	2.09–1.5	1.49–1.0	0.9–0.3	0.29–0

vehicle applications including starting, lighting and ignition, where the goal is to replace the internal combustion engine with a power supply or provide an environmentally-friendly hybrid system that improves the efficiency of fossil fuel engines.

Among these applications, the most suitable for the reuse of mobile phone battery cells are the applications in portable equipment. Table 4 lists the current operation of certain portable electronics and illustrates how it can vary from microamps to more than one ampere.

Actual capacity, considering the density of energy stored per unit, available in a new battery is significantly smaller (about 20–30%) than the theoretical capacity of active materials. Moreover, the actual capacity is even lower than the theoretical capacity because it includes also the weight of non-power producing construction materials. Table 5 shows practical values of energy and voltage density of the electrochemical system. These data are useful for their reuse design, because not all battery models state the capacity of its cells.

NiMH and Li-Ion cells are candidates to replace both ordinary and primary alkaline batteries, and Pb-acid and NiCd ones. To reuse cells with good capacity in electronics whose voltage, battery capacity and size differ from the original specifications of available models, it is important to make a particular study for each case.

We analyzed the various possible configurations of cells considering that the same could be arranged side by side, stacked or lengthwise. As for the type of connection they could be linked in series or in parallel. To estimate the time that the unit should operate, a relationship was established between the capacity of the cells and the power of the equipment. It took into account that cell batteries approved for reuse have internal impedance greater than new batteries. Thus, we used the difference between performance at the end of the slow discharge cycle of new cells and that of those approved with rating A and C, by comparing the readings of the voltage at the cutoff points (considered as 1.10 V for NiMH and 3.25 V for Li-Ion) in percentage points.

2.3. Comparison to new cells

To compare the performance of the cells classified as in operational condition to new cells, chronopotentiometric measurements with slow discharge cycle were made. For that, new cells were used and approved with the concept A and C of NiMH batteries, brand: Nokia, model: BMC-3, 900 mA h and Li-Ion batteries, brand: Nokia, model: BL-5C, 850 mA h.

Table 4
Operating current of some portable electronics.

Equipment	Current consumption (mA)
Calculators (LCD)	<1
Cameras	500–1600
Cell phones	200–800
Camcorders	700–1000
Note book	500–1500
Lanterns	100–700
Remote controls	10–60
Radios/disk players	10–350
TV (portable)	400–700
Toys	
Motorized (remote controls)	600–1500
Electronics games	20–250
Video games	20–200

2.4. Reuse in prototypes

An illuminator for camcorders was designed to use 27 white light LEDs of 7500 mCd divided into three sets of nine each and connected in parallel. As the current drawn by each LED is approximately 15 mA, the current to power the set is approximately 405 mA. Thus, for the selection of battery cells, the requirements were to have a voltage between 3.5 and 4 V and a capacity of at least 1400 mA h for a range of more than 3 h. The battery was designed to reuse two cells Siemens V30145-K1310-X250 Li-Ion approved for reuse with A concept and associated in parallel using welded wires. As the battery was installed on the outside of equipment, in this case there was no size restriction.

Among the technological advantages over traditional light bulbs, the large luminous efficiency of LEDs, the small generation of heat, the possibility of controlling the intensity of light emitted and the limited physical space, motivated their choice as light source in this prototype [24–26].

To maintain constant voltage and operating current, since a small variation of voltage in cells allows the production of a wide variation in current to the LEDs, and consequent great loss of luminosity, we used a current regulator circuit, which provides the needed voltage while maintaining a constant power supply. First the circuit was assembled and tested in a protoboard, and later the final assembly was made by using a drilled copper plate.

Considering the huge amount of portable electronics such as digital cameras, mobile phones, mini games, mp3 players, among others, the possibility of construct a prototype of portable sources capable of supplying the energy of any one of these devices, using cells of rechargeable batteries discarded, which were assessed and approved for reuse, proved to be very convenient and interesting. A power source prototype was designed with an embedded microchip able to provide more precise adjustment of the output voltage. This power source prototype is intended to provide electrical energy and even charge electronic devices up to 5 W of power at 5 V using a standard USB output port.

The battery was designed in order to reuse a set of 7 NiMH cells brand Ericsson model BKB 123 105 approved with concept A and associated in series using welded wires. The battery of this source can be charged from a car electric installation, or using a conventional charger 12 VDC (up to 5 A), providing for this, an input with Jack P2. It was incorporated into the source design: a key to turn on the USB output and a green LED that lights when it is on, and a red LED that lights up when it is being charged by the input P2.

3. Results and discussion

3.1. Assessment of battery cells

At the second stage of the assessment process, where the visual aspect was analyzed, the Li-Ion cells had a proportionally larger amount of approved cells with approximately 13% more than the NiMH ones, which can be attributed to the large amount of old batteries contained in the analyzed population. Yet at this stage, the biggest difference between the proportions of the NiMH models

Table 5
Theoretical and practical values of the major battery systems.

System	Anode	Cathode	Theoretical values				Practical values			
			V	g Ah^{-1}	Ah kg^{-1}	Wh kg^{-1}	V	Wh kg^{-1}	Wh L^{-1}	Ah L^{-1}
Primary batteries										
Common	Zn	MnO_2	1.6	4.46	224	358	1.5	85	165	110
Alkaline	Zn	MnO_2	1.5	4.46	224	358	1.5	145	400	267
Secondary batteries										
NiMH	MH	Ni oxide	1.35	5.63	178	240	1.2	75	240	200
Li-Ion	$LixC_6$	$Li(i-x)CoO_2$	4.1	9.98	100	410	4.1	150	400	98
NiCd	Cd	Ni oxide	1.35	5.52	181	244	1.2	35	100	83
Pb-acid	Pb	PbO_2	2.1	8.32	120	252	2	35	701	351

that were approved was approximately 19.4%, whereas for the Li-Ion it was less than 1.5%.

Table 6 shows a general listing with the results of the cells performance already assessed at different stages of the process with the absolute and relative amounts. According to the results in this listing, from 1197 NiMH cells and 227 Li-Ion cells assessed at the second stage of the process the average of 813 and 195 were approved, which respectively corresponds to approximately 72.2% and 85.8% of total at this stage. It can be observed that the models that had higher relative frequency of approval at the different stages were BKB 193 (123-105) and BL-5C for NiMH and Li-Ion batteries respectively.

Fig. 2 shows a comparison between the average of batteries (set of cells linked in series) and individual cells of the three NiMH models approved and rejected at the stages 2 and 3 of the process. It is observed that the average number of NiMH cells considered approved at the stages 2 and 3 was 73% and 63%, respectively, whereas the number of batteries considered approved at these stages were only 48% and 30%, respectively. This result shows the effect of damaged cells in a battery, in other words, when the cells are linked in series, one damaged cell is enough to compromise the battery performance.

By the third stage of the assessment process, when the remaining voltage was measured in the cells approved at the second stage, the average of only 9% of NiMH cells showed voltage values within the rejection range, whereas the Li-Ion cells showed a higher rejection with the average of 17%. Even the NiMH (BMC-3) model which had the lowest approval with 86,8% showed a slightly higher percentage than the Li-Ion (V30145-K1310-X250) model that had the highest approval with 84.9%.

At the fourth stage, where the cells were subjected to charge and discharge, for both NiMH and Li-Ion cells, only 3% of them were rejected during the cycles. Considering the total of cells assessed until the fourth stage, approximately 63% of NiMH cells and approximately 68% of Li-Ion ones were assessed at this stage. It was considered approved the cells that got the concept A, B or C which corresponded to approximately 40% of NiMH cells and approximately 45% of Li-Ion cells. If the restriction for the approval was higher and only cells with concept A and B were considered approved, approximately 37% of NiMH cells and approximately 32% of Li-Ion cells would be approved. If this restriction was increased further and only the approved cells with concept A were considered, approximately 24% of NiMH cells and approximately 23% of Li-Ion cells would be considered approved.

3.2. Comparison to new cells

The results obtained from the chronopotentiometric measurements (Fig. 3) comparing the performance of new NiMH cells to the performance of the approved cells show that the new cells took

Table 6
Results of the performance of models of NiMH and Li-Ion cells assessed and approved.

Model	Photo (int.)	Stage 1	Stage 2	Stage 3		Stage 4		Total
		Disassemble	Visual aspect	Voltage verification		Cycles performance		Approved
		Quantity analyzed	Rel. (%)	Rel. (%)	Partial total (%)	Rel. (%)	Partial total (%)	Rel. (%)
BMS-3		711	62.2	95.9	59.6	95.9	57.2	36.8
BMC-3		291	72.8	86.8	63.2	97.8	61.9	38.5
BKB 193 (123-105)		195	81.5	88.7	72.3	97.9	70.8	43.6
Partial total		1197	72.2	90.5	65.1	97.2	63.3	39.6
BL-5C		97	86.6	89.3	77.3	96.0	74.2	48.4
V30145-K1310-X250		62	85.5	84.9	72.6	97.8	70.9	48.4
LGIP-411A		68	85.3	74.1	63.2	95.3	60.3	38.2
Partial total		227	85.8	82.8	71.0	96.4	68.5	45.0
Total		1424	78.9	86.6	68.1	96.8	65.9	42.3

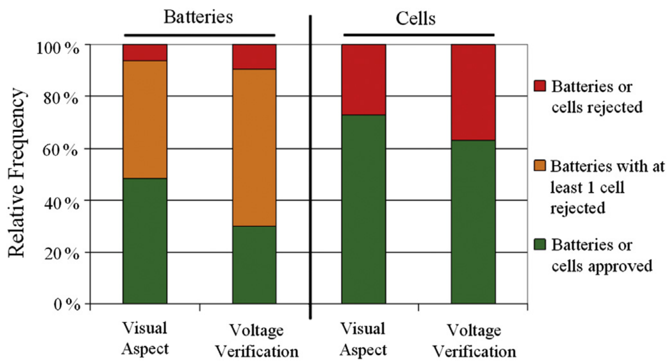

Fig. 2. Relationship between the relative frequency of cells and batteries approved and rejected at the stage 2 and 3 of the assessment process.

about 3 h 15 min to reach 1.15 V, as the approved ones with the concept A and C took about 2 h 40 min and 2 h 05 min respectively, what shows that there is a lower loss of capacity for the concept better obtained.

According to what Fig. 4, again as in the NiMH cells, it can also be seen in the Li-Ion ones a more pronounced difference of behavior between the cells at the level of medium and low charge status. However, the cells approved with concept C showed a voltage of about 3 tens lower than the new ones during the discharge cycle. The new cells took about 3 h 05 min to reach 3.5 V, as the approved ones with concept A and C took about 2 h 25 min and 1 h 30 min respectively.

To estimate the loss of capacity due to the recycling of the cells approved for reuse compared to the capacity of the new ones, the differences of slow discharge to the voltage of the cutoff point were compared (considering 1.1 V and 3.25 V for the NiMH and Li-Ion systems respectively). According to results listed in Table 5, NiMH and Li-Ion cells approved with concept A showed the average of 82.5 and 89.7% of the capacity of their respective new cells. In other words, from the discarded cells tested in this study, approximately 24% of NiMH cells and approximately 23% of Li-Ion cells (approved with concept A) showed more than 80% of the capacity of an identical and new cell.

Experiments conducted with new NiMH and Li-Ion battery cells approved with grades A and C have shown that the variations in internal resistance values depend on the electrochemical system of the battery. Measuring internal resistance in discharge tests to assess the SOC has shown to be a useful tool to estimate the loss of capacity of used cells compared to the capacity of the new ones and allowed to determine that NiMH and Li-Ion cells approved with grade A showed nearly 82% and 90% of the capacity of their respective new cells. Conversely, cells approved with grade C showed nearly 65% and 62% of the capacity of their respective new cells. Cells approved with grade B were not assessed, because it is

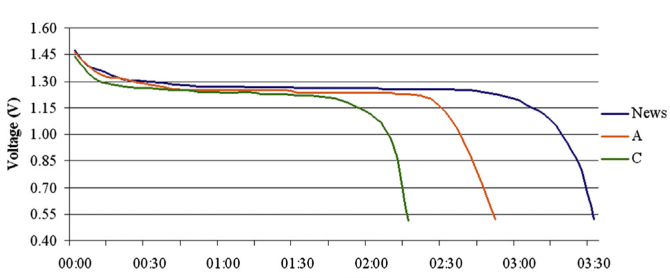

Fig. 3. Slow charge and discharge cycle for new NiMH cells approved with concept A and C.

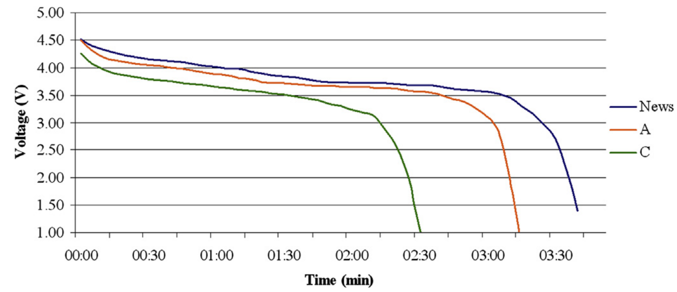

Fig. 4. Slow charge and discharge cycle for new Li-Ion cells approved with concept A and C.

believed that they show an intermediate capacity between those of cell approved with grades A and C.

In view of the curves of battery internal resistance, and considering the charge and discharge cycles, it would be appropriate to suggest that future studies investigate the possibility of using this parameter in the initial tests for approving or rejecting a battery. This suggestion is related to the fact that, at least in the studies conducted for this research in the region from medium to low SOC, a good quality battery tends to show stable internal resistance values, while, in a low quality battery, these same values tend to grow much more faster in this region, which could reduce testing times in the fourth stage, as well as the amount of energy spent on this testing.

In addition to that, since it was possible to observe that from the results obtained by this study, the number of NiMH cells considered approved at the stages 2 and 3 of the selection process was higher than the number of batteries. Since a single battery is composed by several cells linked in series, as long as a cell is defective, the battery performance will be unsatisfactory and it will be considered rejected. This result reinforces even more the proposal of this article, in other words, many batteries discarded by user for showing a possible problem in operation are formed by cells in good working, it means, material with usage potential.

Since the number of batteries produced and sold in stores is huge, this investigation aimed to assess the best possible amount of cells in order to improve sample representativity. This study analyzed three models of each of the two main electrochemical systems of the most commonly collected rechargeable batteries, totaling 1197 cells of NiMH batteries and 227 cells of Li-Ion batteries. It is important to emphasize that the fact that the methodology was not complex is in line with the challenge of promoting an increase in the reuse of cells, an initiative that is extremely important but seldom practiced. To meet the requirement of supplying wide information of their products, the electronic devices manufacturers should put together and provide the necessary information about the products facilities for disassembly and recycling.

3.3. Reuse in prototypes

For the prototype of a LED illuminator, Fig. 5 shows the LED illuminator and its battery comprised of two Li-Ion of the same cells approved for reuse. Because the cells used were approved with the A rating and they were associated in parallel, the resulting battery capacity about 1250 mA h, assuring autonomy capable of supplying the illuminator for just over three hours.

If the equipment is powered by voltages higher than those specified for its best performance, to avoid suffering losses in its operation, such as an excessive increase in temperature, or even irreparable damage, for example, breaking the lamp in a flashlight or damage to transistors in a radio, you can choose to use voltage compatibility circuits to be used together with the batteries.

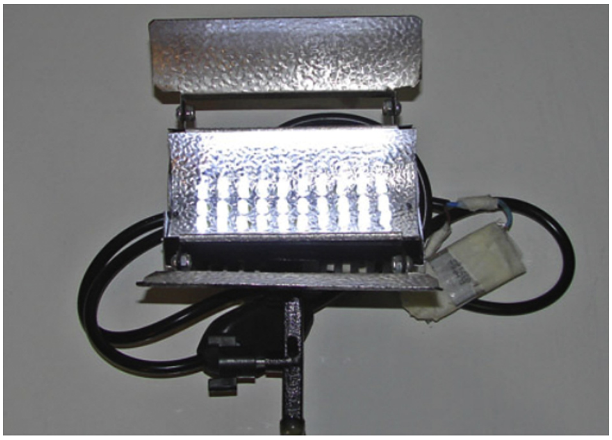

Fig. 5. The LED Illuminator and its battery composed of two cells Li-Ion model V30145-K1310-X250.

The compatibility of voltage levels obtained with the combination of rechargeable cells with those used by various equipment powered by conventional batteries can be done by adding some electronics in the power circuit. For example, to use NiMH cells in a device designed to be powered by two common batteries associated in series, i.e. with operating voltage equal to 3 V, this would require the association in series of three NiMH cells, which results in 3.6 V. This difference in voltage levels can be resolved by placing a silicon diode in series with the 3-cell NiMH batteries. Thus, we obtain the operating voltage of 3 V without causing the discharge of batteries.

The ability to reuse mobile phone battery chargers to recharge the batteries equivalent to those of the relative devices is economical and practical because, as all these are bi-volt chargers, they can be plugged into any outlet, without the risk of burning or malfunction. For other voltage levels (resulting from the combination of more cells) needed for a given application, the construction of special battery chargers can be made from energy sources with low power transformers and appropriate regulators.

We should also mention the possibility of very simple charging circuitry with diodes and resistive or capacitive dividers that could be added to the cell bank itself with terminals available for connection to the mains and the battery of a car. The resistive divider may generate unwanted heat during the charging process, but has a much lower price than a system with a transformer. In some cases, for low charging currents, the use of capacitive dividers can be an economical solution with lower heat generation.

By using a charger that does not have a circuit to identify the status of the charge and finish the recharging operation before exceeding the safety limit, it is important to use a protection circuit with the batteries formed by cells approved for reuse to ensure safe operation, especially when in the hands of the public. This circuit can be formed by a field effect transistor (FET) and also by a fuse that will open if the voltage or the charging temperature of any cell reaches the limits.

If current models of batteries used were standardized in size, as is the case with the AAA, AA and A battery sizes, the possibilities of storing the same for reuse would improve, even in new equipment such as cell phones that could use the battery of the previous model. The battery is one of the most expensive items of the cell phone and could well be used again in new equipment that the consumer purchases if the sizes were standardized, thus avoiding the premature disposal.

Fig. 6 shows the source in operation powering and charging a cell phone in A, and in B open showing inside its battery pack

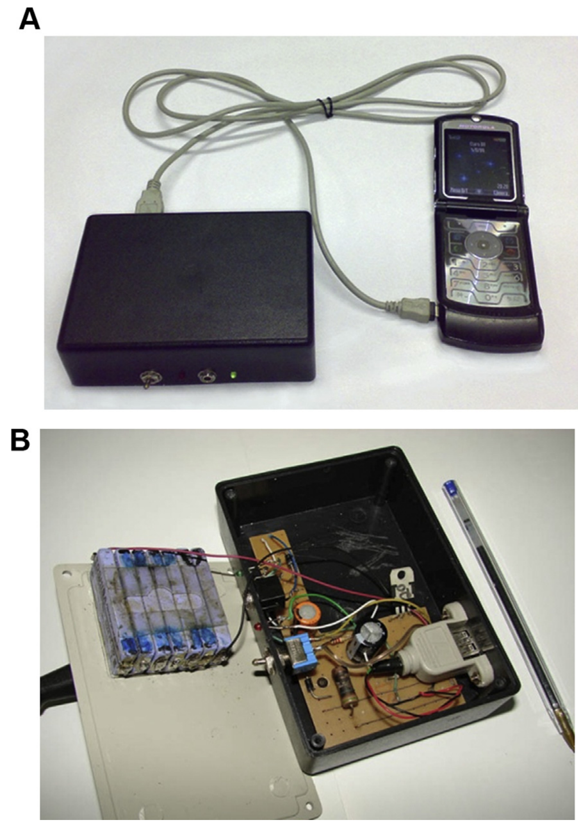

Fig. 6. The Source in operation in operation charging a cell phone in A and open showing your battery consists of 7 cells NiMH model BKB 193 (123-105) in B.

designed in order to use 7 cell NiMH brand Ericsson model BKB 193 (123-105), 900 mA h. Were used cells approved with concept A whose capacity, when new, was 900 mA h, was reduced to approximately 740 mA h, but still ensures a capable of powering, for example, a mp3 player with approximately 0.3 W and consumption of approximately 90 mA h for a time just over nine hours. This source with USB output, allows, with the use of different USB adapters the possibility to power various types of electronic devices.

The proposal for the commercialization of second-hand batteries it is also an interesting idea, but was not the case of the present paper that focused, at first, in the classification of the cells attempting on their reuse in academic activities related to the manufacturing of prototypes and not on a proposal for them to return to the market with the commercialization of them. In order market to accept second-use batteries, safety concept to improve long-term reliability of reuse applications and common causes for battery failure, as, short-circuiting of battery terminals, excessive high rate discharge or charge, voltage reversal, improper charge control, must be taken into account, once these conditions may cause an internal pressure increase within the cells, resulting in an activation of the vent device or a rupture or explosion of the battery.

Because of the increase in the production and use of rechargeable batteries, the reuse and recycling of these batteries is becoming an urgent problem from the point of view of protecting the environment and conserving the resources. It is important to point out that each time a battery is thrown away a new battery needs to be manufactured to replace it even though the first battery had not yet depleted its potential for being used. We intend to bring about a new way to look at it with this study, making society and

the manufacturers aware as to the need to conserve resources based on the proposal of reuse. One should acknowledge the importance of the aim of this research and how challenging it is to promote the efficient use of the limited natural resources related to rechargeable batteries, especially Li-Ion batteries, which requires a joint effort from the scientific and academic community, battery producers, and users.

4. Conclusions

This study analyzed three models of each of the two main electrochemical systems of the most commonly collected rechargeable batteries, totaling 1197 cells of NiMH batteries and 227 cells of Li-Ion batteries. The results obtained with the assessment methodology of cells proposed in this showed that approximately 40% of NiMH battery cells and 45% of Li-Ion batteries cells assessed were in operational condition, with charge capacity between 62% and 90%, when compared to a new cell. These results warn about the waste of natural resources with high aggregated value and propose a critical assessment of the behavior of manufacturers and consumers of this kind of conversion and energy storage device, aiming to establish an alternative environmentally correct to decrease the amount of this kind of electronic waste.

This paper proposes the reuse of cells from discarded NiMH and Li-Ion batteries as strategy applied to the development of prototypes that allows increasing the life cycle of the same and assist designers in building prototypes. Approved cells were reused in the design of a prototype of a lighting fixture and LEDs were chosen as light sources due to their technological advantages over conventional lamps. The prototype of the light fixture with LEDs was designed to work for 3 h. However, other configurations could have been designed to obtain greater autonomy. The prototype of a portable power supplies using cells of rechargeable batteries discarded, which were assessed and approved for reuse, demonstrated able of supplying the energy of many portable electronics devices. In this case were used cells approved with concept A whose capacity, when new, was 900 mA h, was reduced to approximately 740 mA h, but still ensures a capable of powering, for example, a mp3 player with approximately 0.3 W and consumption of approximately 90 mA h for a time just over nine hours. These possibilities presented for the reuse of components such as cell phone batteries comprise an effective and environmentally sustainable alternative, thus contributing to engineering and the environment in hopes of lowering this type of technological waste.

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